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Direct ultrafast laser written C-band waveguide amplifier in Er-doped chalcogenide glass

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Abstract: This paper reports the fabrication and characterization of an ultrafast laser written Er-doped chalcogenide glass buried waveguide amplifier; Er-doped GeGaS glass has been synthesized by the vacuum sealed melt quenching technique. Waveguides have been fabricated inside the 4 mm long sample by direct ultrafast laser writing. The total passive fiber-to-fiber insertion loss is 2.58 ± 0.02 dB at 1600 nm, including a propagation loss of 1.6 ± 0.3 dB. Active characterization shows a relative gain of 2.524 ± 0.002 dB/cm and 1.359 ± 0.005 dB/cm at 1541 nm and 1550 nm respectively, for a pump power of 500 mW at a wavelength of 980 nm.

OCIS codes: (130.3120) Integrated optics devices; (140.3390) Laser materials processing; (320.7130) Ultrafast processes in condensed matter, including semiconductors; (230.7380) Waveguides, channeled.

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1. Introduction

Chalcogenide glasses (ChGs) contain one or more of the chalcogen elements, namely sulfur, selenium, or tellurium from group VI of the periodic table, as a major constituent. Many ChGs are good glass formers with glass transition temperatures well below that of silica-germania-based glasses and hence are relatively easy to process without the need for high temperatures. Glassy chalcogenides are of significant interest due to their good transmittance in the IR region, low phonon energy (which implies low probabilities of non-radiative decay), high optical non-linearity and low vibrational energies [1,2]. Typically, glassy sulphides transmit up to ~11 μm, selenides up to ~15 μm and tellurides beyond 20 μm [3], with third order optical non-linear susceptibilities up to a thousand times that of silica. These optical properties make them good choices for the fabrication of infrared optical components including both integrated devices such as waveguides, and free space components such as infrared lenses.

Within the group of chalcogenide glasses, the sulphides of germanium and gallium are known to form stable glasses in both binary and ternary compositions, which can be drawn into fibers. By doping with erbium these glasses gain additional potential for active photonic devices such as fiber lasers and amplifiers [4]. GeGaS glasses are of particular research interest due to their enhanced rare earth ions solubility. Kasab *et al.* have studied stochiometric and non-stochiometric GeGaS glasses and have shown that the stochiometric glasses are able to homogenously dissolve up to 2 at. % Er^{3+} [5]. Further, Er-doped GeGaS glasses have a strong Er^{3+} intra-4f emission between $^4I_{13/2} \rightarrow {}^4I_{15/2}$ at the telecommunications wavelength of 1.54 µm [6,7].

In the GeGaS glassy network, structural modification affects the photo-luminescence. Deficiency of sulfur creates tetrahedral $[GaS_4]^{1-}$; increasing the Er^{3+} ion concentration acts as a charge compensator for the tetrahedral $[GaS_4]^{1-}$. This determines the solubility of Er^{3+} ions in the GeGaS glassy network [8]. The interesting spectroscopic properties of the glass host enhance the possibility of application of this waveguide in mid infrared photonics, including laser sources and amplifiers.

Femtosecond laser inscription of waveguides in the near infrared region is a well established technique making it a sensible wavelength range to initially investigate with any material. Once waveguides have been successfully fabricated in this range, adaption of their characteristics can then be attempted to allow for the guidance of longer wavelengths.

ChGs are known to exhibit a variety of photo-induced phenomena under illumination with above band-gap radiation [9], and it has been shown that sub band-gap ultra-short light pulses (<<5 ps) can also modify the material properties when tightly focused [10]. Under the correct conditions the energy deposited at the focus by the ultrafast laser can lead to permanent structural changes, including an increase in the material refractive index, confined to a region of the material close to the laser focus [11]. By translating the material through the laser focus this localized refractive index increase can be extended into a dielectric channel waveguide. This direct laser writing (DLW) technology has been proven to produce high quality waveguides in a wide range of materials [12,13], including chalcogenide glass [10,14], and for a variety of applications such as amplifiers and lasers [15,16].

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In this paper, we report the synthesis and fabrication of a waveguide amplifier in an Er-doped chalcogenide glass (GeGaS:Er) by DLW. When pumped using a 500 mW, 980 nm laser diode, the 4mm long waveguide exhibited relative gains of 2.524 ± 0.002 dB/cm and 1.359 ± 0.005 dB/cm at 1541 nm and 1550 nm respectively.

2. Material synthesis

Bulk $Ge_{25}Ga_{5}S_{69.5}$:$Er_{0.5}$ glass has been prepared by a vacuum sealed conventional melt quenching technique. Appropriate quantities of high purity (99.999%) constituent elements are sealed in flattened quartz ampoules under a vacuum of 10^{-6} Torr. The sealed ampoules are subsequently heated in a rocking furnace to a temperature above the melting point of the constituents at a heating rate of 100 °C/h. The ampoules containing the melt are rotated continuously at 10 rpm for 12 hours to ensure homogeneity. They are subsequently cooled in air to obtain bulk glasses. The amorphous nature of the as-prepared samples is then confirmed by X-ray diffraction. The refractive index of this glass and the optical band gap is measured to be 2.41 ± 0.01 at 514 nm using the total internal reflection method [17] and 2.4 eV respectively.

3. Waveguide fabrication

The waveguides are written in a 6mm long GeGaS:Er glass sample using a master oscillator power amplifier Yb-doped fiber laser (IMRA µJewel D400). The repetition rate of the laser is set to 100 kHz and the polarization adjusted to be circular. The pulse duration is 350 fs at the full-width half maximum points and the central wavelength of the laser radiation is 1047 nm which corresponds to a photon energy of 1.18 eV. The laser is focused to a spot of ~1 µm, 100 µm below the substrate surface using a 0.67 NA aspheric lens. To translate the sample it is mounted on computer controlled Aerotech x-y-z air bearing stages. The sample is translated perpendicular to the laser propagation direction to write a waveguide. Waveguides have been inscribed, in groups, with pulse energies from 1.81 µJ down to 100 nJ, decreasing by 15% for each subsequent group. For each group translation speeds of 4 $mm \cdot s^{-1}$, 6 $mm \cdot s^{-1}$, 10 $mm \cdot s^{-1}$ and 18 $mm \cdot s^{-1}$ are used. After fabrication the waveguides facets have been ground to remove any tapering close to the facets and then polished to optical quality. The final waveguide length after polishing is 4.0 mm.

4. Waveguide characterization

4.1 Passive characterization

After polishing the insertion loss of the waveguides to a SMF-28 fiber transmission line has been measured. An amplified spontaneous emission source is connected to an optical spectrum analyzer (OSA is a Advantest Q8384) with a piece of SMF-28 optical fiber. The power spectral density at 1600 nm is taken as a reference. The optical fiber is subsequently broken, cleaved and butt coupled to the waveguide facets with index matching gel used to reduce Fresnel reflections. The insertion loss for the waveguide is defined as the difference in power spectral density at 1600 nm between the signal transmitted through the waveguide and the reference value. The waveguide inscribed with pulse energy of 680 nJ and a translation speed of 6 mm/s is found to exhibit the lowest insertion loss of 2.58 ± 0.02 dB. This insertion loss includes contributions from the fiber-to-waveguide coupling loss, the waveguide propagation loss and the waveguide-to-fiber coupling loss. For single mode waveguides the coupling loss contribution from fiber-to-waveguide must equal the coupling loss contribution from waveguide-to-fiber.

The coupling loss due to mode mismatch has been measured by splicing a piece of large core multimode fiber to the SMF-28 fiber connected to the OSA; it is assumed that since the multimode fiber has a larger core size and higher numerical aperture than the waveguide it will capture all of the light emerging from the waveguide. The coupling loss due to mode

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mismatch is the difference between this measured value and the amount measured when the fiber is re-cleaved so that the emerging light is collected with the SMF-28 fiber. This coupling loss due to mode mismatch has been found to be 0.22 ± 0.02 dB/facet. The contribution to coupling loss from Fresnel reflection is calculated based on the measured refractive index of the GeGaS:Er glass to be 0.28 ± 0.02 dB/facet; this yields a calculated propagation loss of 1.6 ± 0.3 dB for the 4 mm sample. Figure 1 presents a schematic of the experimental setup used to characterize the waveguide performance.

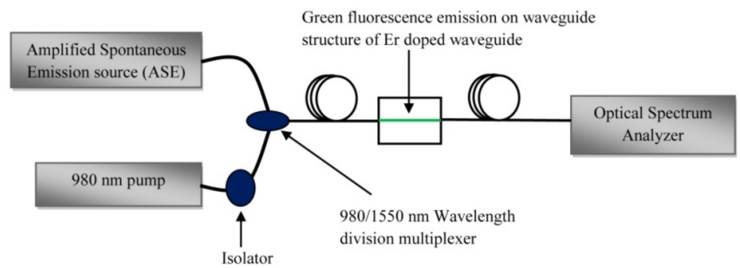

Fig. 1. Experimental setup used to characterize the Er-doped GeGaS waveguides.

After passive characterization, the morphology of the waveguides has been inspected using a white light transmission microscope. A micrograph of the waveguide with the lowest insertion loss is presented in Fig. 2(a). Material modification has been observed for pulse energies greater than 100 nJ and the waveguide morphology is typical of the thermal diffusion regime with limited heat accumulation [18]. This implies that using a higher repetition rate inscription laser may yield a more symmetric modified region and waveguide mode.

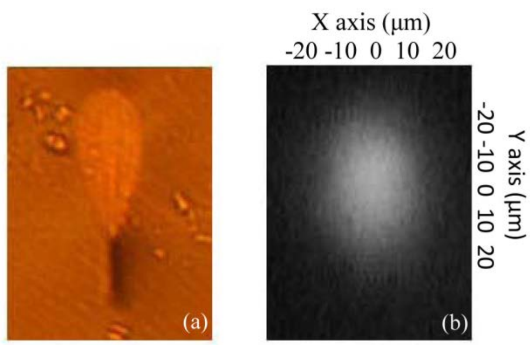

Fig. 2. (a) White light transmission micrograph of the optimum waveguide end-facet. (b) Image of the 1550 nm waveguide mode of the optimum waveguide.

4.2 Active characterization

To measure the waveguide performance as an optical amplifier a fiber coupled 980 nm laser is multiplexed to the ASE source using a 980/1550 nm wavelength division multiplexer (WDM) before coupling in to the waveguide. Another WDM at the output of the waveguide is used to de-multiplex the pump light prior to signal measurement with the OSA. The relative gain of the waveguide is measured as follows: Initially, the fibers are aligned to the waveguide using an attenuated broadband ASE source as the signal. The signal spectrum is measured using the OSA. The pump laser is then enabled and the spectrum is again measured; this spectrum gives the combination of signal, fluorescence and gain. The signal source is then disabled with the

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pump laser remaining on, which is the fluorescence from the waveguide. The relative gain, which is defined as the change in transmission under pumping is given by the relation below:

$$\text{Relative gain}\ (\text{RG}) = 10*\log\left[\left(P_{out}(\text{pump}) - \text{fluorescence}\right) / P_{out}(\text{no pump})\right], \quad (1)$$

where P_{out} (pump) is the signal from the waveguide when the pump is present, fluorescence is the fluorescence emission due to the pump when no signal is present and P_{out} (no pump) is the signal from the waveguide when no pump is present.

Figure 3 shows the relative gain spectra of the Er doped GeGaS glass waveguide with a pump power of 500 mW. It can be seen that there is 1.0099 ± 0.0008 dB of gain at 1541 nm and 0.5435 ± 0.002 dB of gain at 1550 nm; this corresponds to a relative gain of 2.524 ± 0.002 dB/cm and 1.359 ± 0.005 dB/cm respectively. Although a relative gain 2.5 dB has been reported previously in chalcogenide glass waveguides which are fabricated in sputtered film and in erbium-ytterbium doped phosphate glass direct laser written waveguides [15,19], this is, to the best of the authors' knowledge, the first demonstration of gain in a chalcogenide glass waveguide amplifier fabricated by DLW technology at telecommunications wavelengths. Importantly, due to the low phonon energy of the glass host, Er emissions at 2 μm, 2.75 μm, 3.6 μm and 4.5 μm should be accessible, making mid infrared amplifiers and sources at these interesting wavelengths realisable.

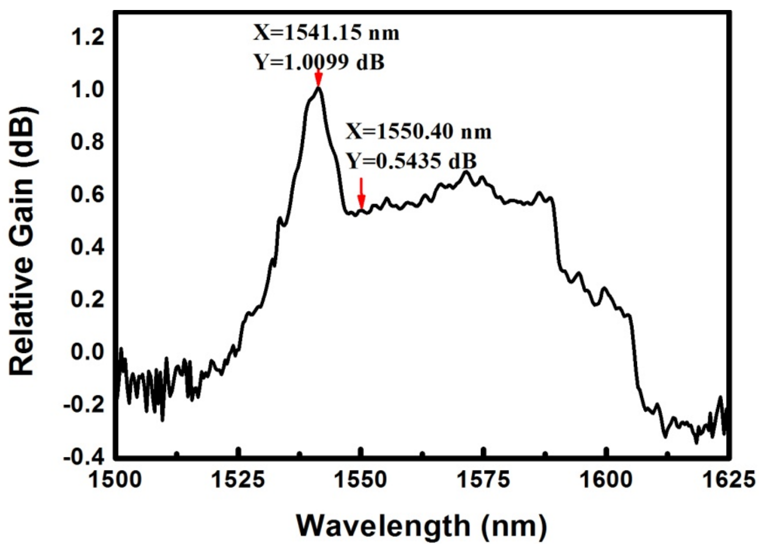

Fig. 3. The relative gain spectrum of the Er-doped GeGaS glass waveguide with a pump power of 500 mW at 980 nm.

In comparison to other low phonon energy host media, including silicon and fluorozirconate based materials, the transmission range (up to 8 μm) and stability of GeGaS ChG offer significant advantages [20].

5. Conclusion

In this paper we detail the fabrication and characterization of a waveguide amplifier in Er-doped GeGaS glass by direct laser write technology. A significant relative gain of 1 dB or 2.5 dB/cm at 1541 nm is demonstrated for a device with an insertion loss of 2.58 dB. Further optimisation of the inscription parameters is expected to decrease propagation losses and in combination with longer waveguides, significant net gain can be achieved. Future work will be focused on establishing low loss guiding in the mid infrared spectral region allowing for the fabrication of waveguide amplifiers for the mid infrared spectral region.

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